SOLAR WIND DISTURBANCES IN THE OUTER HELIOSPHERE
CAUSED BY SUCCESSIVE SOLAR FLARES FROM THE SAME ACTIVE REGION

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ABSTRACT

Solar wind disturbances caused by successive flares from the same active region are traced to about 20 au, using the modeling method developed by Hakamada and Akasofu (1982). It is shown that the flare-generated shock waves coalesce with the co-rotating interaction region of the interplanetary magnetic field, resulting in a large-scale magnetic field structure in the outer heliosphere. Such a structure may have considerable effects on the propagation of galactic cosmic rays.

Introduction

During the last decade, a considerable progress has been made in understanding the solar wind flow and the propagation of solar wind disturbances in the heliosphere (Shea et. al., 1977; Dryer and Steinolfson, 1976; Dryer and Tandberg-Hanssen, 1980). A somewhat different approach from the standard hydrodynamic and MHD methods was considered by Hakamada and Akasofu (1982) who devised a method analogous to an aerodynamic technique in simulating some aspects of the disturbed solar wind with a fair accuracy. They construct first a steady state pattern for the so-called 'two-sector' or 'two-stream' situation. For this purpose, they assume that the distribution of the solar wind speed on the source surface (a spherical surface of radius of 2.5 R_o) has the minimum speed (V=300 km/sec) along the heliomagnetic equator which is assumed to be inclined by 20° with respect to the heliographic equator; the speed is assumed to increase toward higher latitudes in both the northern and southern hemispheres. The resulting magnetic field configuration in the equatorial plane is the well-known co-rotating structure which consists of two 'spiral arms' (the corotating interaction region), as faster winds interact with slower winds.

Propagating Flare Disturbances

(a)   Two successive flares from the same region

Effects of solar flares are introduced in this co-rotating structure by adding a high speed flow from a circular area, centered around a solar flare, on

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the source surface. In the circular area, the flow speed is assumed to have a Gaussian distribution of the 'half-width' σ; the flow speed V_F at the center of the circular area is assumed to vary in time as $V_F = V_{Fmax} \cdot t \cdot e^{-(t/\tau)}$; thus, a flare is characterized by six parameters, the latitude (θ), longitude (ϕ) and the onset time (T_F) of a flare, the maximum flow V_{Fmax} (km/sec) at the center of the circular area of its size parameterized by $\sigma(^\circ)$, and the time variation of V_{Fmax} by τ(hr). For the method of introducing effects of a solar flare, see also Hakamada and Akasofu (1982). The first flare is located at the magnetic equator ($\theta = 0^\circ$) and the longitude $\phi = 0^\circ$, namely on the crossing point of the positive x-axis through the source surface. This particular flare is parameterized by the maximum wind speed $V_{Fmax} = 800$ km/sec, $\tau = 12$ hrs and $\sigma = 60^\circ$.

The second flare is introduced 48 hours (2 days) after the first flare. It is assumed that the same active region is responsible for both flares, which have rotated by $\phi = 28.3^\circ$ from the time of the first flare. The second flare is characterized by a faster flow $V_{Fmax} = 1000$ km/sec, the same growth-decay curve ($\tau = 12$ hrs) and a narrower extent ($\sigma = 20^\circ$) than the first one.

Figure 1a shows the disturbance patterns (< 5 au) in the ecliptic plane at T=0, 1.5, 3.5 and 7.0 days after the onset of the first flare. In this particular example, the shock wave associated with the second flare caught up with the first shock wave on about the 6th day. Note that the spiral structure continued to rotate, while a part of the inner part of the spiral structure was destroyed by the first shock. On the 8th day both shocks reached one of the spiral arms. Behind the shocks, a new spiral arm begins to reform rapidly.

Figure 1b shows the disturbance pattern within a radial distance < 25 au, T = 12, 24, 36 and 48 days after the onset of the first flare. On the 24th day, both shocks reached the second co-rotating structure. Meanwhile, the new spiral arm is clearly established behind both shocks. As the shocks propagate further, the inner spiral structure reforms rapidly and expands outward. On the 48th day, both shocks reach the third co-rotating structure, forming a complex magnetic field structure in the outer heliosphere.

Note that from the 12th day to the 48th day, the co-rotating structure has rotated ~ 1 1/3 times. If there is no solar flare disturbance, two spiral arms pass by regularly at any fixed point in the figure every 27 days, causing two distinct increases of the solar wind speed and the magnetic field magnitude. However, the shock waves caused by the solar flares disturb considerably such a regular pattern. In fact, on the 48th day, two co-rotating structures and the two shocks pile up at a radial distance of about 17 au and it is no longer possible to identify individual co-rotating structures and the shocks.

(b) Six successive flares from the same active region

In this particular example, we assume an extremely active region which produces six successive flares in a period of 10 days. The six flares are parameterized as follows:

Flare 1 $T = 0$, $\phi = 0^\circ$, $\theta = 0^\circ$
$V_{Fmax} = 800$ km/sec, $\tau = 12$ hrs, $\sigma = 60^\circ$

Flare 2 $T = 2.0$ days, $\phi = 28.3^\circ$, $\theta = 0^\circ$
$V_{Fmax} = 1000$ km/sec, $\tau = 12$ hrs, $\sigma = 20^\circ$

Flare 1 $T_F=0, \phi=0°, \theta=0°$
         $V_F=800, \tau=12, \sigma=60°$
Flare 2 $T_F=48, \phi=28.3°, \theta=0°$
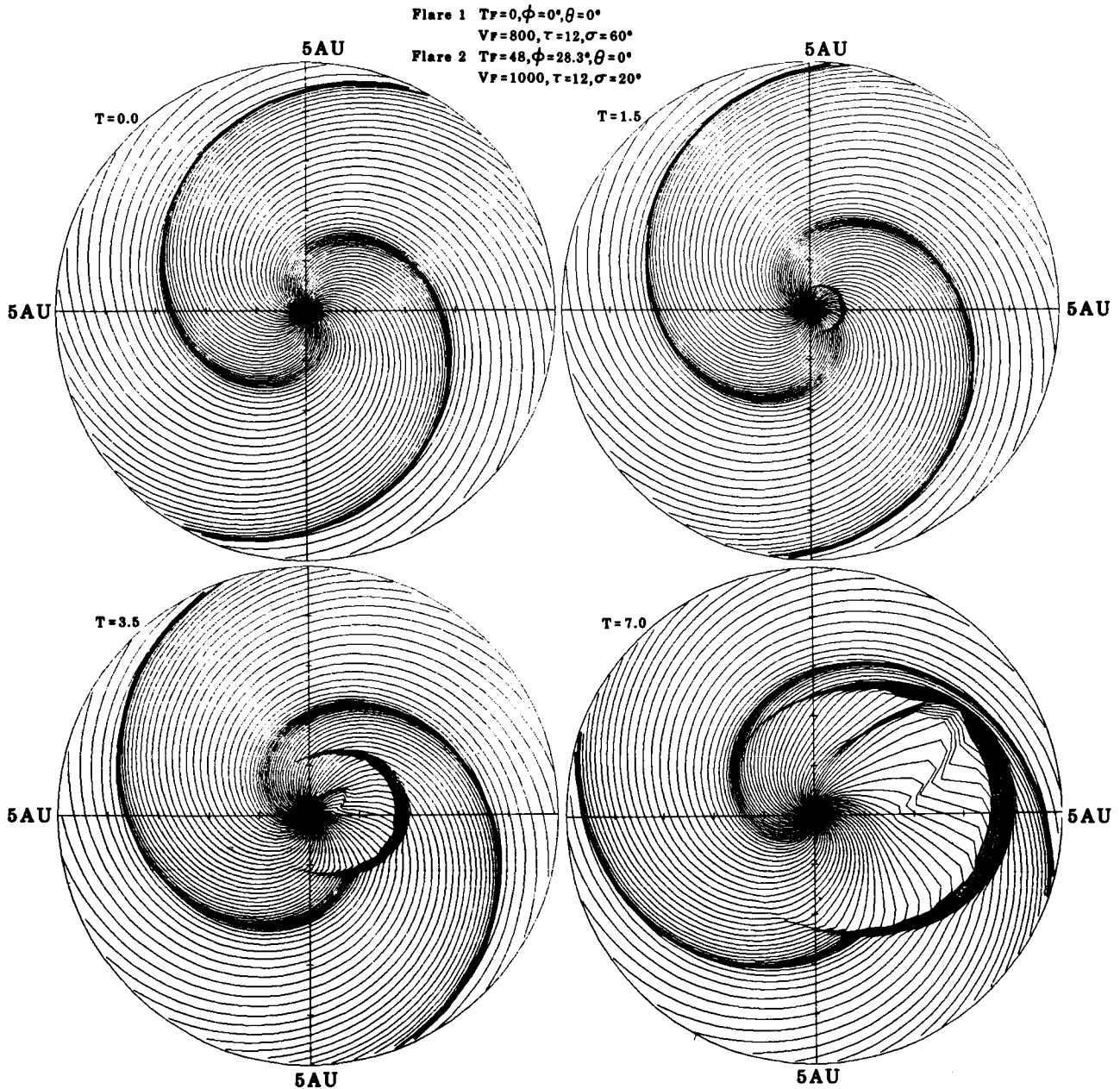 $V_F=1000, \tau=12, \sigma=20°$

Figure 1a. Solar wind disturbances caused by two successive flares in the ecliptic plane, separated by 48 hours, from the same active region. The figure shows the propagating structure at T=0 (onset), 1.5, 3.5 and 7.0 days after the onset of the first flare. The outer limit of each circular area is at 5 au.

Flare 1 $T_F = 0, \phi = 0°, \theta = 0°$
          $V_F = 800, \tau = 12, \sigma = 60°$
Flare 2 $T_F = 48, \phi = 28.3°, \theta = 0°$
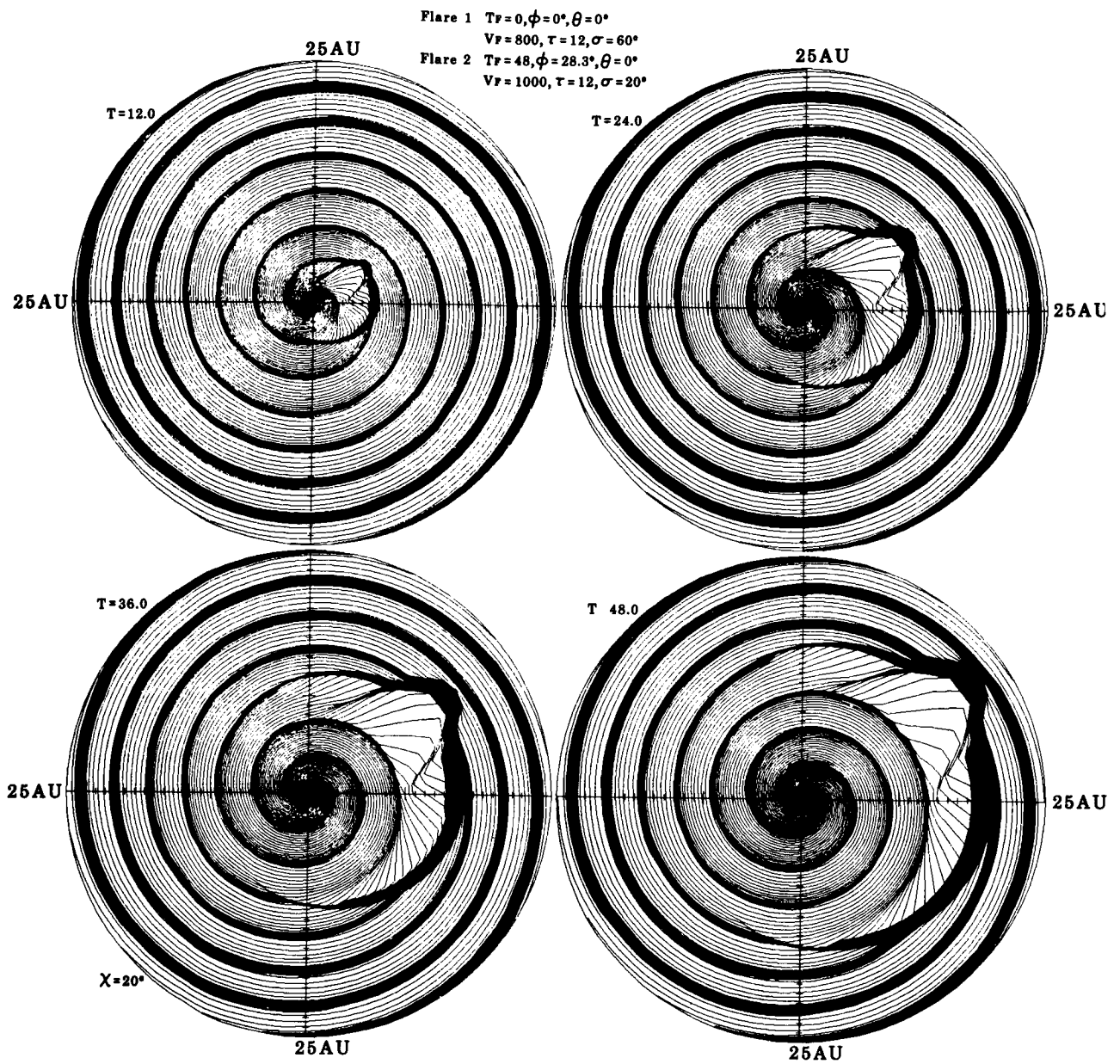 $V_F = 1000, \tau = 12, \sigma = 20°$

Figure 1b. Continuation of Figure 1a, showing the propagating structure at T = 12, 24, 36 and 48 days. The outer limit of each circular area is at 25 au.

Flare 3   T = 4 days, ϕ = 56.7°, θ = 0°
            V_{Fmax} = 800 km/sec, τ = 12 hrs, σ = 60°

Figure 2 shows the propagating disturbance pattern at T=7, 10, 17, 15, 19 and 25 days after the onset of the first flare. One can see that all the shock waves coalesce with the spiral patterns, forming an extensive magnetic field structure. It is quite likely that such a structure will have considerable effects on the propagation of galactic cosmic rays in the outer heliosphere.

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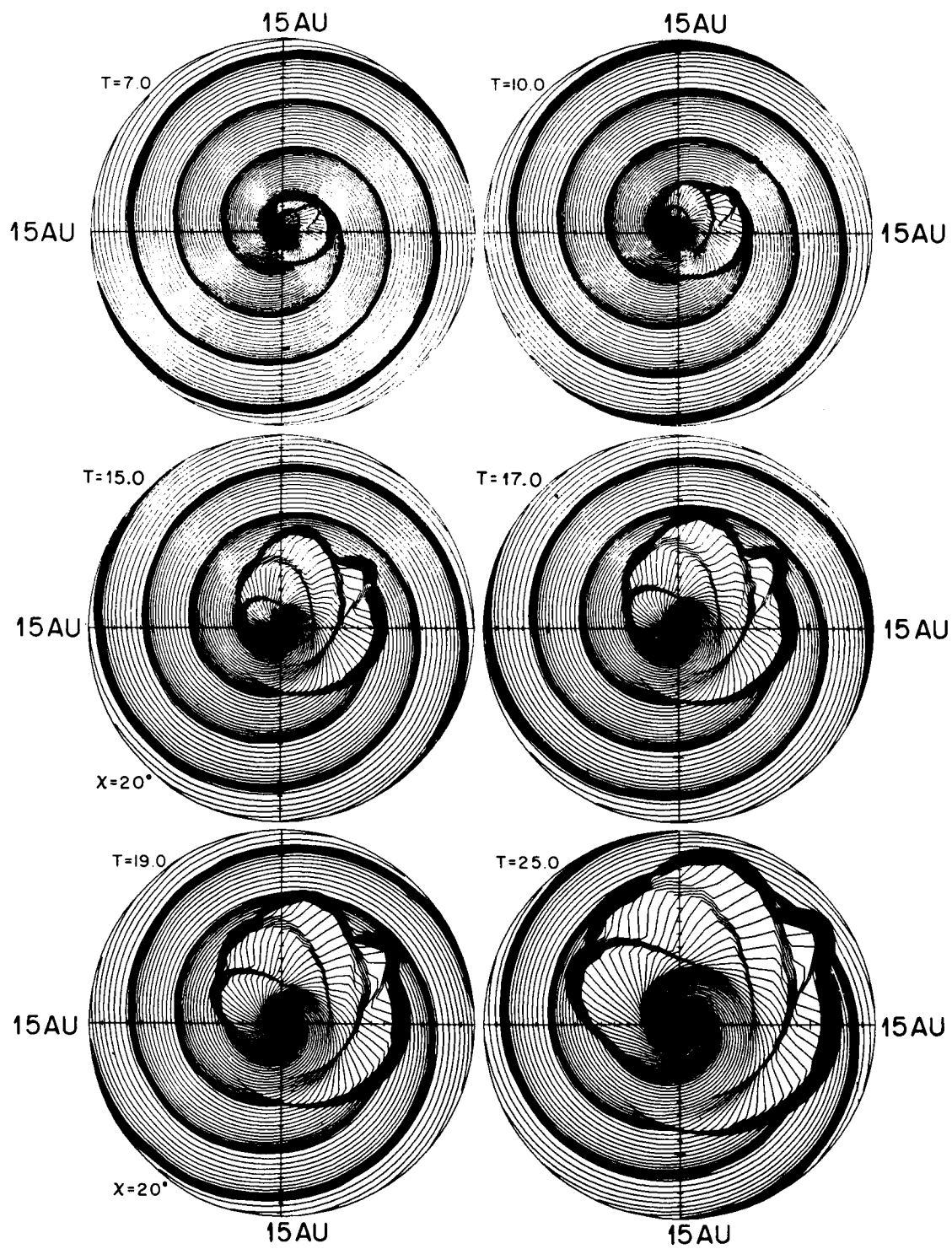
Figure 2.   Solar wind disturbances caused by six successive flares during a period of 10 days.   The figure shows the propagating structure at T = 7.0, 10.0, 17.0, 15.0, 19.0 and 25.0 days after the onset of the first flare.   The outer limit of each circular area is at 15 au.

Comments on "Solar wind disturbances in the outer heliosphere,
caused by successive solar flares from the same active region",

by Akasofu and Hakamada

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In this paper, a kinematic modeling technique (Hakamada and Akasofu, 1982) is used to simulate the interaction of transient flows with a two-sector corotating flow to large heliocentric distances. The input transients, which are characterized by several parameters, have peak speeds in the range of 800-1000 km/s. Hence the corotating flows constitute an inhomogenous slower-speed background, into which the transients continually penetrate. Thus, by 10 AU in the authors' last example (which involves six separate flares), the interaction of the transients with the corotating flows as well as with each other produces a very complicated jumble of magnetic fields. It is further asserted that such contorted magnetic topologies should have important consequences for galactic cosmic ray transport.

With this last point, I have no particular quibble, other than to mention that the basic concept has been around for nearly two decades. Parker (1963), for example, broached the general idea in his book, though he did not offer very specific estimates as to where substantial magnetic complexes would form or what their dimensions might be. Only recently, in fact, have enough detailed data appeared to permit some assessment of the validity of the idea (e.g., see McDonald *et al.*, 1982; Burlaga *et al.*, 1982; and Burlaga *et al.*, 1983).

So the questions to ask are: How faithfully does this modeling technique, with all its obvious practical advantages, simulate the flow interactions? To what extent is it quantitatively accurate? Are there any regions where it fails even in a qualitative sense?

In considering these questions, it must be recognized from the outset that accuracy of the sort usually associated with a full MHD model is not required for the authors' stated purposes. On the other hand, for a model to rank as an effective tool, it must still successfully predict the gross features of the flow: e.g., the heliocentric distance where the major structures interact, the spatial scale of the resultant interaction region, the rate at which CIRs expand, the approximate magnitude of the field enhancements, etc.

It is my contention that the model of Hakamada and Akasofu (1982) meets even these relaxed criteria only in a limited parameter range and only over a fairly restricted span of heliocentric distances. Further, I will argue that the particular examples presented by the authors are in general violation of these limitations and their results are thus compromised.

To begin, let us be clear as to the physical content of their model. The Hakamada and Akasofu (1982) formulation is first and foremost a purely kinematic description, i.e. the evolution is entirely determined by the input velocity variations; the material in no way exerts either a gas pressure or magnetic field force. What is especially poignant is the way the authors handle those regions where fast material overtakes slow. It is inevitable that at some point the fluid elements must begin to overlap, corresponding to a shock in the dynamic case. Here the authors invoke a parameterized curve-fitting method to keep the usual R-t diagram from becoming double-valued (see Sec. 1.3 and 2.3 in Hakamada and Akasofu, 1982). The parameters are chosen such that the resultant V-t or V-R curves resemble some particular observed streams or dynamic model calculations. However, the predictive value of any model is measured by its ability to cope with a wide variety of input flows (such as are encountered in the real solar wind) under a single parameterization. That is, in practical applications one is forced into picking one parameterization that will be in effect throughout the simulation and will have to accurately describe the evolution of all flow states therein. In general, it will not be possible to tinker meaningfully with the parameters after the fact, since if the model is being used in the predictive mode, there is obviously nothing to calibrate it against.

A single parameterization of the type used by the authors may well allow them to mimic a few well-chosen streams, as they have demonstrated. And, indeed, were all solar wind streams more or less alike, such an approach might be viable. However, it hardly needs any emphasis that solar wind flows differ markedly in speeds, field strengths, densities--in fact, over the entire gamut of flow parameters. And all the interesting large-scale interaction phenomena--the rate at which CIR's expand, the rate at which shocks form and decay, the lateral expansion of a directed blast wave, etc.--all depend sensitively upon the local properties of the ambient medium and the input shock strength, i.e. they are inherently dynamic in nature. It is of paramount importance to recognize that the authors' parameterization of shock propagation, for example, is based solely upon kinematic considerations. The speed jump is first computed from kinematics and the ad-hoc parameterization, then density and field are chosen to satisfy flux conservation. Thus, while the Rankine-Hugoniot relations are in some sense satisfied, the thermodynamic and magnetic properties of the medium play no role in the determination of the shock speed. In view of these considerations, then, it is difficult to see how any single parameterization can suffice for the range of flow states studied by the authors. At least, they have not demonstrated such a capability.

That being said, we must now ask how all this specifically impacts the authors' results. The answer will be split into three parts : the model's treatment of the corotating structure alone; its treatment of isolated impulsive flows into an ambient medium; and, its treatment of the interaction between transient and corotating flows.

First, with regard to purely corotating flows, recent observational and theoretical efforts (Burlaga, 1983; Pizzo, this conference) seem to concur that by about 10 AU all the fast material in high-speed streams has been pretty well consumed in the interaction and that the subsequent evolution is governed by large-scale pressure-wave dynamics. In this regime, a kinematic approach is totally irrelevant. The authors are able to maintain an identifiable stream structure to large heliocentric distances only through careful manipulation of input conditions at the inner boundary: their input structure is longitudinally very broad, with the gentlest of velocity gradients. Thus their CIRs do not even form until about 7 AU and are still reasonably compact at 20 AU (see Fig. 1.5 in Hakamada and Akasofu, 1982). In consequence of all the observational experience gained through Pioneer and Voyager, the authors' background flow therefore appears highly unrealistic, to say the least.

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Next, in the case of an isolated, impulsive transient penetrating into a uniform ambient flow, there are two major shortcomings in this model. First, since all features of the shock propagation in the model are solely contingent upon the input velocity structure, there is no distinction, really, between strongly driven shocks and simple blast waves, which are known to have quite different evolutionary properties (e.g. Hundhausen and Gentry, 1969) . Again, the parameterization in the model could be adjusted for one class, but then it would be inappropriate for the other. Second, an important feature of multi-dimensional shock propagation is that the forward shock expands near the sun to cover a much broader angular span than does the input disturbance, while the reverse shock remains fairly localized within the driver gas (e.g. D'Uston et al., 1981). The lateral expansion of the forward shock front is a purely dynamic phenomenon and has great significance for the field structure. In the kinematic model, of course, the shock is confined to the input angular cone and there is simply no way to reproduce the important spreading effects.

Finally, when transients and corotating streams are allowed to interact, it has long been known that the density (and presumably magnetic) structure of the ambient corotating flow plays at least as large a role in the interaction as does the velocity structure (Heinemann and Siscoe, 1974; Hirschberg et al., 1974). Shock speeds and transit times are thus going to be very poorly modeled in the authors' formulation, particularly when the disturbances are traced over many AU and across many intervening structures.

In light of all these considerations, it is hard to see how the authors' model can possibly provide a quantitatively adequate representation of the flow systems presented in this paper. Their corotating background flow is quantitatively unrealistic inside about 10 AU and is not even qualitatively appropriate beyond that point. And, owing to the serious deficiencies in their treatment of the very complex transient-corotating interaction as outlined above, it is evident that their quantitative estimates for the important physical properties of the flow (the location, dimensions, and amplitude of the resultant magnetic structures) at large heliocentric distances must be regarded with critical suspicion. It is to be stressed that what is at issue here is not a dry technical debate over some trifling 10-20% discrepancies among alternative methods of calculation. Rather, I contend that the kinematic model, as in the grossly over-extended application witnessed in the authors' treatise, is susceptible to such large quantitative error that the accompanying Figures are best viewed as little more than computer-generated schematics.

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